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CONTROL OF MYOELECTRICAL RESPONSES THROUGH REINFORCEMENT

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A classic experiment by Hefferline, Keenan, and Harford (1959) showed that small thumb-twitches, imperceptible to the subject, can be controlled by the consequences of terminating and/or postponing aversive noise. These findings were further investigated in three experiments reported here. Experiment 1 replicated the original study. Experiment 2 was a control study in which stimulus changes were presented as in Experiment 1, but independently of the responses. Under these conditions the response rate varied over a large range with no systematic relation to experimental events. The increments in response rate reported by Hefferline et al. were within the present range of variation, suggesting that conditioning in the earlier study may have reflected a consistency in the direction of change rather than an increase in rate beyond the baseline range. In the present experiment, however, the rate increase was absolute. In Experiment 3, analog rather than binary changes in stimulus conditions were used as reinforcement. Under these conditions, the rates of subjects whose responses were conditioned fell from 78% (in the previous experiment) to 31%.

Key words: operant conditioning, myoelectrical response, naive human adults

Hefferline, Keenan, and Harford (1959) reported that myoelectrical activities—specifically small twitches of a thumb muscle—may be operantly conditioned, without the subject's being able to report the changes that take place. In that study, the operant response was myoelectrical activity of the eminence thenar of the left hand that accompanied a small twitch of the thumb, not knowingly controlled by the subject. The operant response was reinforced by briefly turning off noise that was superimposed on recorded music selected by the subject. If no response was emitted, the noise continued. The schedule of reinforcement allowed each response to terminate the noise, or to postpone it. Hefferline et al. observed in some subjects an increase in the response rate, and they attributed this to the contingent relation between the subject's myoelectrical activity and the acoustic events. These conclusions strongly support the thesis that operant conditioning is not limited to "voluntary responses" but works efficiently also with "involuntary activities" (e.g., Miller, 1978).

The work of Hefferline et al. (1959) has been given great theoretical importance. Together with other studies (Basmajian, 1963, 1979a, 1979b; Carlsöö & Edfeldt, 1963; Harrison & Mortensen, 1962) it forms the basis of most investigations of biofeedback, especially with muscular responses, and its therapeutic applications (Budzynski, 1979; Davis, Saunders, Creer, & Chai, 1973; Johnson & Garton, 1973; Marinacci & Horande, 1960; Yates, 1980). Despite its importance, the experiment has not so far been replicated. The present study was conducted to do this. First, the experiment was replicated with certain technical improvements; then, a control experiment was conducted, in which the stimulus changes were the same as in the previous experiment but without their contingent relation to behav-

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Table 1
Recapitulation of the distribution of subjects exposed to control and conditioning experiments, compared to subjects of Hefferline et al.

		HEFFERLINE AND AL.		LAURENTI- LIONS AND AL.		
PROCEDURE		CONTROL	COND.	CONTROL	COND. I	COND. II
TOTAL NUMBER OF SUBJECTS		0	24	37	36	35
OPERANT RESPONSE NOT FOUND	NUMBER		12	24	18	22
	REASONS: EMG HYPERACTIVITY			4	2	1
	EMG HYPOACTIVITY			7	11	1
	EMG BASELINE ARTIFACT			13	5	20
OPERANT RESPONSE FOUND	NAIVE SUBJECTS		6	13	18	13
	NON NAIVE SUBJECTS		6	0	0	0

ior. Finally, effects of changing the schedule of reinforcement were also investigated. In one experiment (Conditioning I), a binary-type schedule (Lamoureux, Joly, & Bouchard, 1977) was used, whereby the subject's myoelectrical activities were divided into two parts: the operant response, which was reinforced, and all the others, which were not reinforced. In a second experiment (Conditioning II), the schedule of reinforcement was of the analog type: The intensity of the noxious stimulus was changed as a function of the difference between the criterion operant in Conditioning I and the emitted response. All the experiments presented were conducted with naive subjects, in that they were not told the aim of the experiment.

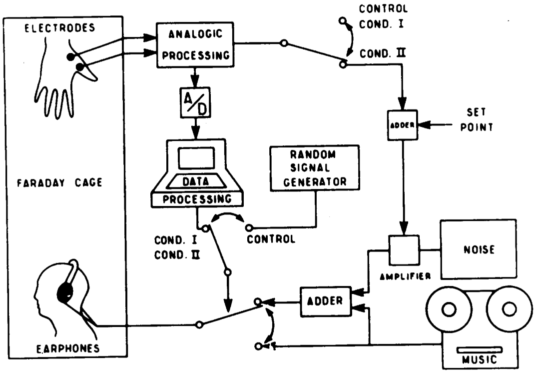

Fig. 1. Equipment configuration for Control, Conditioning I, and Conditioning II experiments. A binary-type schedule of reinforcement was used in the Conditioning I experiment and an analog-type schedule was used in the Conditioning II experiment. A/D is analog-digital converter.

METHOD

Subjects

Subjects were 108 university students. They were told that the experiment concerned the study of the effect on muscular activity of noise superimposed on music. Each subject received 50 French francs at the end of the experiment. Table 1 shows the numbers of subjects exposed to the different procedures.

Apparatus

The apparatus was an automated version of that described by Hefferline et al. (1959). Figure 1 shows the general arrangement of the apparatus, which consisted of the following: (a) two surface silver chloride-chloride electrodes (Beckman 650437) — one attached to the palmar base of the thumb, the other to the external edge of the eminence thenar approximately 1 cm from the palmar electrode. Active electrodes were affixed to the skin by an adhesive collar and by a sticking strip. The ground electrode was attached to the wrist. Recording sites were prepared by abrading and cleansing the skin. An electrode paste (Beckman 201210) was used as an electrode-skin interface. (b) An analog system for preprocessing myoelectrical signals that were (i) amplified by a factor of 10^6 and filtered for 10 to 120 Hz activity (differential amplifier ECEM, Type A6, driving point impedance 2100 megaohms at 10 Hz); (ii) rectified and demodulated; and (iii) integrated in successive periods of 315 ms. At the end of each period, the value of the integrated signals was stored in analog memory and the integrator was reset. Figure 2 shows a typical example of these conversions of electrical activity. (c) An analog-digital converter (Bur-Brown SDM856R, 12 bits). (d) A microcomputer (CBM Commodore, 32 k-bytes, Basic language, acquistion programmed in Assembler language), which ensured the following: (i) prescribed length of sequences for each experiment; (ii) detection and numbering of myoelectrical activities that were consistent with the criteria of the operant response defined by Hefferline et al. These were related to their amplitude, which had to be between 1 and 3 μV above the basic level recorded at the electrodes, and to their frequency of occurrence. The initial frequency had to be between 0.5 and 2 responses per minute (in practice, the operant response was defined by an upper and a lower limit); (iii) computing of various data for each subject: operant response frequencies during successive phases of 10 min (noted F_i, $i = 1, 2, \ldots 7$); the mean value F_m and standard deviation s of F_i values ($i = 2, 3, \ldots 7$); the relative frequency F_m/F_1 (the reference value being the frequency during the initial 10-min interval); the total number of operant responses

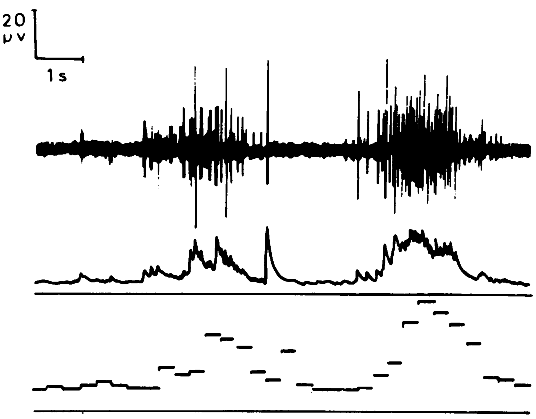

Fig. 2. Analog processing of the myoelectrical signal. Top line: amplified and filtered signal; middle line: rectified and demodulated signal; and bottom line: final values of the integrated signal. Integration periods were 315 ms.

emitted at time t, N_t; and the relative increment $(N_t - N_1)/N_1$; (iv) the control of the two positions of a relay (music with noise or without noise) in Conditioning I and Conditioning II experiments. This control of the relay was determined by the schedule of reinforcement. In the control experiment, the schedule of reinforcement was replaced by a random-control procedure, programmed by means of a random-signal generator. In this procedure, listening conditions were similar to those of the conditioning experiments but the auditory events were independent of responses.

Three devices completed the apparatus: a tape recorder, a function generator that produced a 90-Hz sound at a constant level (equivalent to those of the musical signals), and a system that mixed the noise and musical signals. Mixed signals were connected to one of the relay inputs, the second input being connected to the output of the tape recorder alone. In the Conditioning II experiment, an analog device was inserted between the function generator and the mixing system in order to modulate the aversive sound intensity. This device included a variable amplifier whose gain varied with the logarithm of the difference between the operant response and the baseline level of myoelectrical activity emitted by the subject.

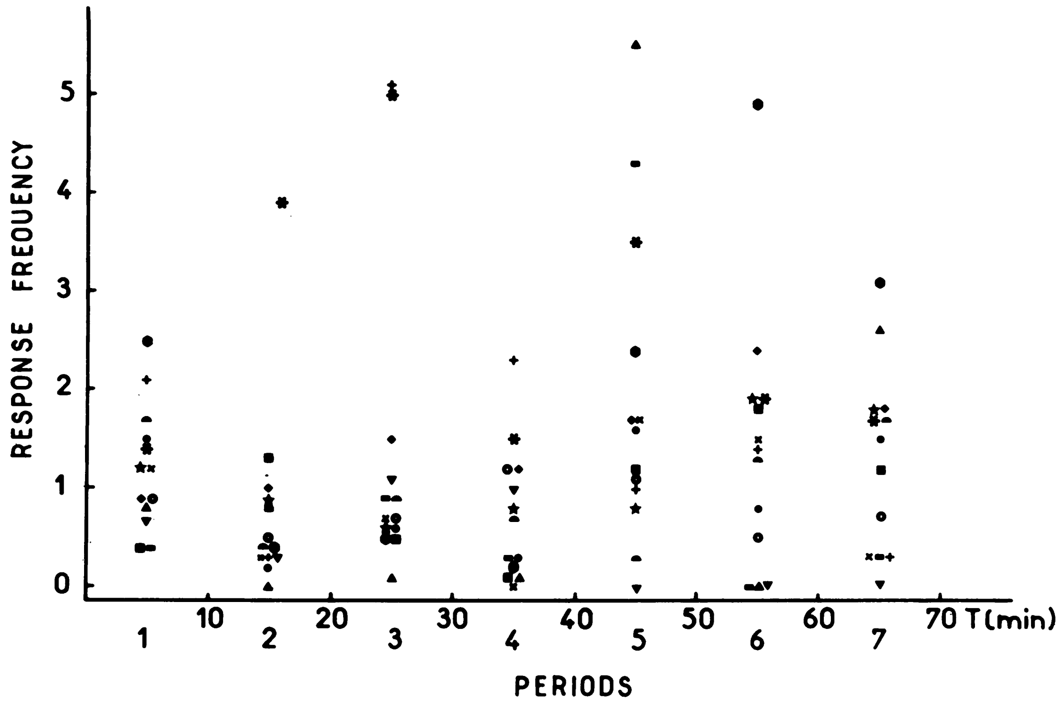

Fig. 3. Pseudo-operant response frequencies in control subjects during successive 10-min segments of the experimental session. For each period, the frequency is expressed in number of pseudo-operant responses per minute. Each of the 13 symbol types represents one of the 13 control subjects.

Procedure

The three experiments (Control, Conditioning I, Conditioning II) followed similar procedures. After attachment of the electrodes, the subjects were seated inside a sound-attenuating shielded cubicle. The subject was seated in a comfortable position in a reclining chair and was instructed to remain still. Before the start of each experiment, the subjects listened to recorded music. During this acclimation period, myoelectrical activity stabilized, and the experimenter selected the particular myoelectrical activity level that was to be used as the response (operant or pseudo-operant response). The duration of each subject's session was approximately 70 min. In the Control experiment, for the first 40 min subjects listened to recorded music without any noise, and for the last 30 min they were presented an arbitrary alternation of music with or without noise, independent of any myolectrical activity. In Conditioning Experiments I and II, during an initial period of 10 min with music only, the baseline operant response F_1 was calculated. Then the schedule of reinforcement was set up for two successive periods of 30 min separated by a few minutes' intermission. During these two periods, the operant response turned off the aversive noise for 15 s, or, if the noise was already off, postponed the resumption of noise for 15 s.

RESULTS

Control Experiment

Figure 3 shows the performances of the 13 control subjects. For each subject, frequency of the pseudo-operant response was highly variable during the first 40 min (periods 1 to 4). These unsystematic variations continued through the last 30 min (periods 5 to 7), during which noise was presented intermittently. It should be stressed that the amplitude of these variations did not increase.

Conditioning I

Table 2 shows the performances of the 18 subjects in the Conditioning I experiment. For each subject, the mean operant response frequency F_m, calculated for the 60 min of condi-

Table 2

Operant response frequencies before and during conditioning for the 18 subjects exposed to the binary schedule of reinforcement (Conditioning I). F_1 = initial frequency (in number of operant responses per min) for the first 10-min period; F_m and s = the mean and standard deviation, respectively, of response rates during conditioning periods 2 to 7. The three symbols indicate the subjects whose data are presented in Figures 4 and 7.

SUBJECTS	★ 1	2	3	4	5	6	7	8	9	■ 10	● 11	12	13	14	15	16	17	18
F_1	0.7	0.6	0.7	0.7	0.4	0.4	0.4	0.5	0.6	0.4	0.7	0.8	0.4	0.3	1	0.6	1	0.6
F_M	3.0	10.1	3.6	4.0	1.2	2.7	3.7	1.7	1.3	4.9	29.0	5.6	16.3	6.4	2.2	2.1	1.6	2.9
s	3.1	8.2	3.1	3.3	0.6	0.9	1.3	1.0	1.1	0.8	31.6	2.5	12.0	6.1	3.3	2.3	1.3	3.1

tioning, was higher than the initial frequency F_1, calculated for the 10 min that preceded the onset of the schedule of reinforcement. The standard deviations of the F_i were quite large in relation to their corresponding means. Thus, the operant-response frequency varied extensively during the experiment; however, Figure 4 indicates that the successive frequencies F_i did not increase systematically after the first one with the contingency in effect.

Figure 5 shows the relative increments of operant responding in Conditioning I, along with the relative increments of pseudo-operant responding in the Control experiment. Looking at the final values of this relative increment $(N_t - N_1)/N_1$, there was little overlap between the two groups. Thus, for 14 of the 18 subjects in the Conditioning I experiment, the relative increment of responding was higher at the end of the experiment than for the 13 control subjects. This may be considered evidence of conditioning, inasmuch as it shows that the increase of operant-response frequency was not attributable to the noise per se. Figure 5 also shows that the rates of increase in responses were irregular in all subjects exposed to Conditioning I.

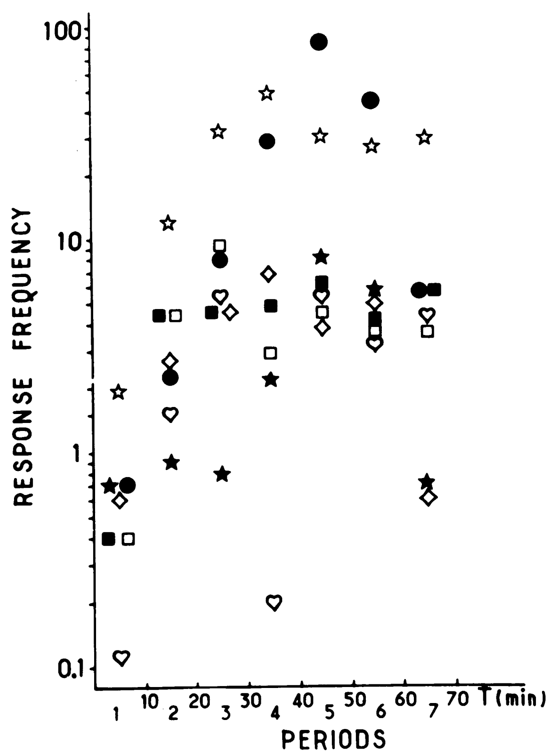

Fig. 4. Response frequency ($\log_{10}$ scale) as a function of within-session time, for 3 subjects exposed to Conditioning I (filled symbols) and 4 subjects exposed to Conditioning II (unfilled symbols).

Conditioning II

The results for the 13 subjects in the Conditioning II experiment are listed in Table 3, which shows that F_m was lower than F_1 in 3 subjects. Figure 4 indicates unsystematic fluctuation throughout conditioning of the F_i measures, as in Conditioning I. The results of Conditioning II can be compared with those of the Control experiment in Figure 6. Only 4 subjects in Conditioning II made more re-

Table 3

Operant response frequencies before and during conditioning for the 13 subjects exposed to the analog schedule of reinforcement (Conditioning II). F_1 = initial frequency (in number of operant responses per min) for the first 10-min period. F_m and s = the mean and standard deviation, respectively, of response rates during conditioning periods 2 to 7. The four symbols correspond to subjects whose data are presented in Figures 4 and 7.

SUBJECTS	1	2	3	♥ 4	♦ 5	6	7	8	9	10	□ 11	12	☆ 13
F_1	0.6	1.4	0.3	0.1	0.6	0.9	3.4	1.7	0.9	0.3	0.4	0.9	1.9
F_M	0.5	3	0.7	3.2	4.0	2.4	1.7	1.9	0.3	0.5	4.8	2.0	30.0
s	0.3	1.5	0.7	2.1	2.1	1.5	1.3	1.7	0.4	0.4	2.3	2.8	12.6

sponses than the maximum for the Control subjects. The slopes of these cumulative curves were irregular, as in the preceding results.

The results of the three different procedures can be compared in Figure 7. It appears that, using the criterion of conditioning defined above, the Conditioning I procedure was the more efficient; that is, more of the subjects in Conditioning I showed higher relative frequencies of responding than did the subjects in the other two experiments.

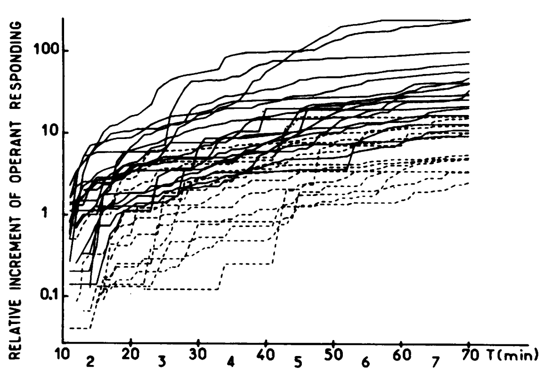

Fig. 5. Cumulative curves, in semi-log coordinates, for the 13 control subjects (dashed lines) and for the 18 subjects exposed to Conditioning I (solid lines). The relative increment of operant responding was calculated according to the formula $(N_t - N_1)/N_1$, where N_1 is the number of operant (or pseudo-operant) responses emitted during the initial observation period (10 min), and N_t is the cumulative number of operant (or pseudo-operant) responses emitted by instant t during the periods 1 to 7.

DISCUSSION

The experimental arrangement used in this study was an automated version of the one used by Hefferline et al. (1959). Automation relieved the experimenter of having to detect and judge

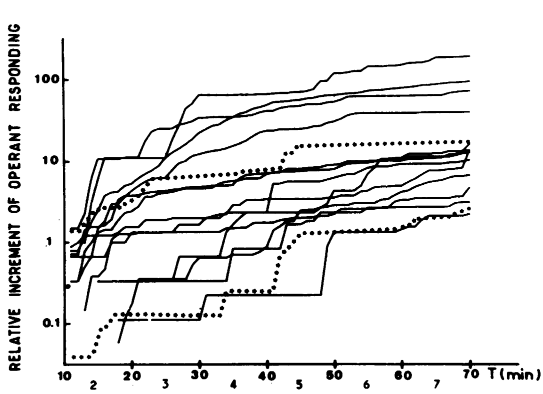

Fig. 6. Cumulative curves in semi-log coordinates of the 13 subjects exposed to Conditioning II (solid lines). The two dotted lines represent the maximum and the minimum of the relative increment of pseudo-operant responding in control subjects in successive minutes. The data were calculated as for Figure 5.

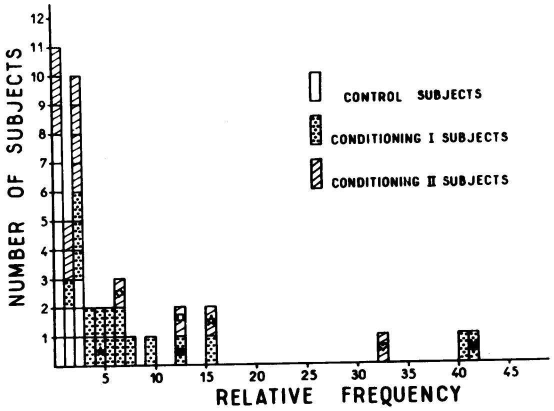

Fig. 7. Frequency histogram for Control, Conditioning I, and Conditioning II subjects. The relative frequency is the rate F_m/F_1, where F_m is the mean frequency of operant (or pseudo-operant) responding during Conditioning I, Conditioning II, or Control (in number of operant responses per minute); F_1 is the initial frequency (in number of operant responses per minute). The symbols in this histogram show the subjects whose data are given in Tables 2 and 3.

the operant response, and thus probably prevented errors that might result from the wavering attention or delayed reaction time of the observer. This improvement in the apparatus did not affect the principle of the experiment as it was conceived by Hefferline and his colleagues.

Table 1 enables comparison of the present results with those of Hefferline et al. About 59% of the subjects in our three experiments could not be used. The rate of rejected subjects is important because this presents considerable difficulties in performing such experiments. There were two bases for rejecting subjects. First, it is impossible to quantify precisely the myoelectrical activity of some subjects because of slow random deflections of their electromyographic baseline without correlated muscular contractions. The origin of this type of artifact may be sweat-gland activity that induces significant changes in skin resistance (Cohen, 1979). It is a classical problem in surface electromyography, made worse in our case by the very high amplification of the signals required by the nature of the experiment. Second, in some subjects it was impossible to select just one myoelectrical activity satisfying the criteria defined by Hefferline et al.; these criteria seem to be very restrictive. This second problem arises in two ways: hyperactivity or hypoactivity relative to these criteria (i.e., relative to the electromyographic signal amplitude and the initial response frequency of the operant response). The proportion of subjects rejected for these reasons was somewhat higher than that reported by Hefferline et al., who considered fewer subjects and did not give detailed reasons as to why they presented the results of only 12 of the 24 selected subjects.

Table 1 also provides information that has not been studied in detail—namely, the experimental naivety of subjects. The present subjects were given no information about the purpose of the experiment and no signal was provided as feedback. The subjects did not report any attempts to produce thumb contractions. Brief, informal interviews, conducted at the end of each experiment, confirmed that in these respects all subjects remained naive throughout the experiment. In the Hefferline et al. study, on the other hand, only 6 of the 12 subjects were comparably naive. Among others, three had, in addition to the auditory feedback described above, a visual feedback stimulus. These features complicate the interpretation of that earlier research.

The results of the Control experiment indicate that even without any feedback, and under good listening conditions, the frequency of the pseudo-operant response varied unsystematically. Therefore, the range of these variations is an important indicator of the effects of closing the feedback loop connecting auditory comfort to the myoelectrical activity of the subject. In order to estimate this range, an extension of the initial period of the conditioning procedure was necessary. During this period, we set the reference value of the operant-response frequency. In the Hefferline et al. experiment, this period was only 10 min. In view of the present results, it appears that in that earlier study the baseline-response frequency may not have been established sufficiently to provide a reliable reference value. Nevertheless, the present replication of that study (Conditioning I) provides, a posteriori, further support for the earlier conclusions.

If the period for estimating the operant-response frequency (F_1) is restricted to 10 min, it might be concluded that the responses of all 18 subjects in Conditioning I were conditioned. For each subject, the operant-response frequency (F_m) increased with respect to the initial frequency (F_1). But if these results are compared with those of the Control experiment, it is seen that only 14 of the 18 subjects showed an increase. For the 4 others, the frequency was of the same order as that of the Control subjects. This latter finding, when considered with the first one, strongly indicates the effectiveness of the operant conditioning procedure as conceived by Hefferline et al. In the present study, the Control and Conditioning experiments were conducted on two distinct groups. Future studies should seek confirmation within subjects, replicating the procedure with an increase in the length of the initial period.

In both the Control and Conditioning I experiments, the frequencies of the pseudo-operant and operant responses were highly unsteady. These fluctuations were partly due to the characteristics of the response selected, which is a random and infrequent activity. These features were amplified by the analyzing system of the myoelectrical signal. This methodological difficulty contributed to the persistence of these fluctuations in the conditioning situation, because, of course, an operant response that was not registered was not reinforced. This problem may be reduced by an increase of the sampling frequency of the myoelectrical signals, an approach that was not possible in our case because of the limited capabilitites of the microcomputer. Moreover, the very conditioning procedure creates conditions that favor such fluctuations. Because the aversive noise was absent for relatively long periods when the subject responded with frequencies above 1 per 15 s (length of the reinforcement of each operant response), the procedure may have resulted in some unsteadiness of the behavior. Under these conditions, the alternations of clear music/noisy music, necessary for acquisition at least in the initial period, disappeared, resulting in low frequencies of the target response.

The Conditioning II procedure was considerably less efficient than Conditioning I, inasmuch as only 4 of the 13 subjects of this group showed notable changes in frequency of responding. With an analog schedule of reinforcement, the subjects may optimize their auditory comfort according to their own criteria. In particular, they may significantly reduce their discomfort by producing myoelectrical activities quantitatively close to the operant response. Thus, reduction of discomfort in this way may, for some subjects, have a reinforcing effect very similar to that of the total disappearance of the noise. The subjects in our final experiment may have produced not only the operant response, but also responses the dimensions of which are close to it. In order to obtain detailed evidence concerning this possibility, evaluation of a broad range of myoelectrical activities during the total length of the experiment should be considered. Hefferline and Keenan (1961, 1963) and Sasmor (1966) carried out similar studies, but their conclusions were not determinative. It is worth noting that large fluctuations of the operant-response frequency were also observed in Conditioning II subjects.

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